

# CIRCUMFERENTIAL MEASUREMENT OF TUBULAR MEMBERS

## BACKGROUND OF THE INVENTION

### 1) Field of the Invention

The present invention relates to apparatuses and methods for measuring a  
5 tubular member and, more specifically, for measuring one or more cross-sectional  
characteristics of the tubular member.

### 2) Description of Related Art

Tubular members such as pipes, ducts, and the like are used in various  
applications, for example, as transport passageways through which gases can be  
10 delivered for heating, ventilation, and air conditioning. In other applications, pipes,  
ducts, and other tubular members can also be used to deliver liquids, such as water,  
waste liquids, and the like. In the aircraft industry, tubular members are provided as  
ducts in environmental control systems (ECS) of modern commercial aircraft. An  
ECS and, hence, the ducts therein, provides air throughout the cabin of the aircraft in  
15 order to provide air as required for the respiratory needs of the occupants, to clear  
contaminants and odors from the cabin air, to control the temperature and humidity of  
the cabin environment, and to provide adequate cabin pressure. Air can also be  
delivered throughout the aircraft for de-icing of the aircraft, for heating of the cargo  
area of the aircraft, for pneumatic systems, and for cooling hydraulic and electrical  
20 systems.

The tubular members used for ducts, such as for the ECS of an aircraft, are  
typically formed of composite or metallic materials. Common composite  
reinforcement materials include fiberglass (BMS 8-80, 8-139, or 8-226), graphite  
(BMS 8-168), and Kevlar<sup>®</sup> (BMS 8-264), a registered trademark of E.I. du Pont de  
25 Nemours and Company. These reinforcement materials, which can be provided as  
sheets, fibers, or the like, can be preimpregnated with epoxy or polyester resin, which  
hardens when subjected to heat and pressure. Alternatively, the reinforcement  
materials can be reinforced with thermoplastic materials such as polyetherimide

(PEI), which is available under the trade name Ultem<sup>®</sup>, a registered trademark of General Electric Company. In either case, ducts formed of composite materials can be lightweight and strong. Alternatively, the tubular members can be relatively thin-walled structures that are formed of metals such as steel.

5           Tubular members, such as composite ducts, are typically dimensionally tested, e.g., by measuring the circumference or diameter of the member to see if the cross-sectional size of the member matches the desired size. For example, the inner or outer diameter of the tubular member can be measured using a gauge, calipers, micrometers, and the like. However, due to the flexible nature of composite materials  
10           and many thin-walled structures, the tubular members can flex during testing, thereby reducing the accuracy of the measurement. Alternatively, the tubular member can be measured by extending a flexible measuring tape around the circumference of the member. In the case of a “pi tape,” the measurement units marked on the tape are adjusted by the value of the pi constant, i.e., the marked units reflect the linear length  
15           of the tape divided by pi. Thus, an operator can quickly determine the diameter of the tubular member by extending the tape around the tubular member and reading the diameter from the circumferential markings on the tape. However, regardless of the units provided on the measuring tape, the measurement made therewith is dependent on the placement of the tape and the reading that is taken by the operator. Thus, like  
20           the other mechanical measuring devices listed above, the accuracy of the tape is limited by the ability of the operator.

          In yet another conventional method of measurement, an electronic coordinate measuring machine is used to determine relative coordinate positions for several points around the circumferential perimeter of the tubular member. The coordinate  
25           positions are then used to determine the cross-sectional size of the member, e.g., by using a “best-fit” technique in which the coordinate positions are matched up with an equation describing a best-fit circle, and a circumference of the member is thereby approximated. The coordinate measuring machine can be capable of very accurately determining the positions of the several points, but the circumference determined by  
30           the machine is only an approximate measurement. In particular, if the cross-sectional shape of the member is not circular, the best-fit circle will not accurately correspond to the cross-sectional shape of the member, and the accuracy of the dimensions determined with the machine can be decreased.

Thus, there exists a need for an apparatus and method for accurately measuring the cross-sectional characteristics of a tubular member formed of a thin-walled or otherwise flexible material. The apparatus should be capable of accurately determining at least one characteristic, such as the diameter or wall thickness, of the tubular member, even if the cross-sectional shape of the member does not define a perfect or uniform polygonal shape such as a circle.

#### SUMMARY OF THE INVENTION

The present invention provides an apparatus and method for accurately measuring the cross-sectional characteristics of a tubular member. The apparatus includes cooperable template members that define an adjustable aperture for receiving the tubular duct. A measurement device detects the adjustment of the members and thereby measures one or more characteristics of the tubular member such as the diameter. The apparatus can urge the tubular member to a reference shape, e.g., if the tubular member in an unconstrained configuration defines an irregular or nonuniform cross-sectional shape. Further, the measurement can be performed accurately with a reduced dependence on the technique of an operator.

According to one embodiment of the present invention, the apparatus includes first and second cooperable template members, which cooperably define the aperture having a cross-sectional reference shape of the tubular member, e.g., a circle. Each of the first and second template members can include two or more plates configured in a spaced relationship. The first and second template members can be connected by a hinge connection and thus rotatably adjustable between open and closed positions. An urging device is configured to apply a predetermined force to the members to urge the members toward the closed position. The measurement device is configured to detect the relative position of the first and second template members, e.g., by measuring a gap between the first and second template members opposite the aperture from the hinge connection. Thus, the measurement device, which can be an electronic device configured to automatically measure the relative position of the template members, measures the relative adjustment of the members between the open and closed positions. The measurement device can also be configured to determine a diameter of the tubular member.

The present invention also provides a method for circumferentially measuring a tubular member. The method includes inserting the tubular member into an aperture defined by the first and second cooperable template members, and adjusting at least one of the template members to at least partially close the aperture, for example, by rotating one of the template members about a hinge connection between the template members. The tubular member is urged, e.g., by applying a predetermined force, to a cross-sectional shape corresponding to the reference shape of the aperture such as a generally circular cross-sectional shape. The relative position of the first and second template members is measured, and a cross-sectional size, such as a diameter, of the tubular member is determined according to the relative position of the first and second template members. The position of the template members can be measured by measuring a gap therebetween, e.g., at a position opposite the aperture from the hinge connection. An electronic measurement device can be configured to measure the relative position of the template members.

Further, the present invention provides an apparatus and method for measuring the tubular member at a plurality of circumferentially spaced locations. For example, measurement devices can be configured to contact the tubular member at the circumferential locations when the aperture is closed so that each measurement device provides an output that is characteristic of a contact force between the measurement device and the tubular member. The measurement devices can be configured to detect a force, pressure, or a stress that is representative of the stiffness of the tubular member. Thus, the variation of the wall thickness of the tubular member can be determined accordingly.

## BRIEF DESCRIPTION OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is a perspective view of an apparatus for circumferentially measuring a tubular duct according to one embodiment of the present invention;

Figure 2 is a top view of the apparatus of Figure 1, shown in an open configuration;

Figure 3 is a perspective view of a tubular duct that can be measured with the apparatus of Figure 1;

Figure 4 is an elevation view of the apparatus of Figure 1, shown in a closed positioned with the tubular member configured therein for measuring;

5        Figure 5 is an elevation view of an apparatus for measuring a tubular duct according to another embodiment of the present invention;

Figure 5A is an enlarged partially cutaway view of a portion of the apparatus of Figure 5 illustrating two of the measurement devices thereof;

10       Figure 6 is a partial section view of the apparatus of Figure 5, as seen along line 6-6 of Figure 5A;

Figure 7 is a partial elevation view of the apparatus of Figure 5, shown in a closed position with the tubular member configured therein for measuring;

Figure 8 is a graph illustrating the magnitudes of the outputs provided by the measurement devices of the apparatus of Figure 5;

15       Figure 9 is a graph illustrating the thickness of the wall of the tubular member at various circumferential locations as measured at a particular longitudinal position using the apparatus of Figure 5; and

Figure 10 is a graph illustrating the eccentricity of the tubular member as measured at various longitudinal positions using the apparatus of Figure 5.

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#### DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different  
25       forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring now to Figure 1, there is shown an apparatus **10** for measuring a  
30       tubular member **14** (Figure 3) according to one embodiment of the present invention. The apparatus **10** can be used for measuring a variety of tubular members **14**, such as pipes, ducts, tubes, and the like, which can be formed of metal, plastic, thermoplastic or thermoset composite materials, and other materials. Advantageously, the tubular

members 14 can be flexible, such as thin-walled metal members or tubular members 14 formed of flexible polymeric or composite materials. Such tubular members 14 can be used for duct passages in heating, ventilation, and air conditioning systems in aircraft, buildings, and the like. Additionally, the tubular members 14 can be used in  
5 a variety of other applications, for example, as flexible pipes for transporting other fluids such as for transporting steam, irrigation, drainage, or delivery of gas, oil, and the like. Further, the tubular members 14 can be used as structural members in building construction, for sports or medical devices, and the like.

The apparatus 10 is configured to circumferentially measure the tubular  
10 member 14 to determine one or more cross-sectional characteristics of the tubular member 14. For example, the apparatus 10 can be configured to support the tubular member 14 about a circumference of the tubular member 14 and determine a diameter of the tubular member 14. The diameter or other measurements of the tubular member 14 can be determined at various positions along the length of the member 14,  
15 e.g., at each of the longitudinal positions  $D_1$ - $D_8$  shown in Figure 3. While the apparatus 10 shown in Figure 1 is structured to measure a tubular member 14 having a generally circular cross section, it is appreciated that the apparatus 10 in other embodiments can be used to measure tubular members 14 having other cross-sectional shapes including elliptical or oval shapes, rectangular shapes, contoured  
20 shapes, or nonuniform shapes.

As illustrated in Figure 1, the apparatus 10 includes first and second template members 20, 30 that cooperably define an aperture 40 extending therethrough for receiving the tubular member 14. The first template member 20, which is connected to a base 12, includes a support member 22 and two plates 24, 26 that are connected  
25 to opposite sides of the support member 22. Similarly, the second template member 30 includes a support member 32 and plates 34, 36 connected to opposite sides thereof. The plates 24, 26, 34, 36 can be connected by bolts 18 to the respective support members 22, 32 such that the plates 24, 26, 34, 36 can be removed for maintenance, repair, or replacement, e.g., with plates of different configurations to  
30 define different sizes or shapes of aperture 40. In other embodiments of the present invention, each template member 20, 30 can be formed of multiple additional members, or each template member 20, 30 can be a unitary structure (that is, a

template member need not have two separate plates, but may have a single plate or other structure that defines a portion of the aperture).

5 The first and second plates **24, 26, 34, 36** of each template member **20, 30** can be generally similar in configuration. That is, the first and second plates **24, 26** of the first template member **20** can define a similar arcuate portion of the aperture **40** so that the first template member **20** corresponds to a portion of the curved cross section of the tubular member **14**. Similarly, the first and second plates **34, 36** of the second template member **30** can define a similar arcuate portion of the aperture **40** so that the second template member **30** corresponds to the remaining cross section of the tubular member **14**. Thus, the first and second template members **20, 30** cooperably define the aperture **40**, which corresponds to a reference or nominal cross-sectional shape of the tubular member **14**. Alternatively, the first and second plates **24, 26** of the first template member **20** can be define dissimilar portions of the aperture **40**, and the first and second plates **34, 36** of the second template member **30** can be correspondingly dissimilar so that the two template members **20, 30** in combination define the aperture **40**.

Thus, with the template members **20, 30** configured as shown in Figure 1, the aperture **40** extends through the apparatus **10**. The aperture **40** can be perpendicular to the plates **24, 26, 34, 36**, as shown, or the aperture can be disposed at an angle thereto. Also, the plates **24, 26, 34, 36** can define surfaces **25, 27, 35, 37** at the aperture **40**, which can be smooth cylindrical surfaces, as shown, or can define a V-shape or other grooves, ridges, or contours. At least one of the first and second template members **20, 30** is preferably adjustable so that the aperture **40** can be opened and closed. For example, the first and second template members **20, 30** can be connected at one end by a hinge **42** so that the second template member **30** can be rotated between an open position (Figure 2) and a closed position (Figures 1 and 4). In other embodiments, the template members **20, 30** can be otherwise adjustably connected, e.g., by rails or posts that extend from one of the members **20, 30** and are slidably received and supported by the other member **20, 30**. In the open position, the aperture **40** is open to more easily receive the tubular member **14**. The second template member **30** can be adjusted manually, e.g., using a handle **38** provided thereon. Alternatively, in other embodiments of the invention, an actuator, spring, or the like can be provided to achieve or facilitate the relative adjustment of the template

members 20, 30. The template members 20, 30 are preferably formed of stiff materials such as aluminum or other metals. Holes 39 can be formed in one or both of the template members 20, 30 to reduce the weight of the members 20, 30 and reduce the energy required for adjustment.

5           A measurement device 50 is configured to detect the relative position of the first and second template members 20, 30. For example, the measurement device 50 can be a conventional electronic position detection device such as a gauge that includes an adjustably extendable probe 52 that is biased by a spring to an extended configuration. The probe 52 is extendable from a probe housing 54 that is mounted  
10       on the first template member 20, and a flange 56 on the second member 30 is structured to contact the probe 52 when the second template member 30 is closed relative to the first structural member 20. Thus, the probe 52 is configured to be extended by the spring from the probe housing 54 when the second member 30 is adjusted toward the open position and retracted into the probe housing 54 as the  
15       second template member 30 is adjusted toward the closed position. A digital monitoring device 58 electrically communicates with the probe 52 and is configured to detect the extension or retraction of the probe 52 and thereby measure the relative position of the two template members 20, 30. Other measurement devices can alternatively be used including, e.g., mechanical gauges, linear measuring references,  
20       optical measuring devices, and the like.

          One or more shock absorption devices 60 can also be provided to reduce the shock on the measurement device 50 during closing of the template members 20, 30. For example, each shock absorption device 60 can include a spring and a damper that are connected to the first template member 20 and configured to be acted on by the  
25       flange 56 or another portion of the second template member 30 when the second template member 30 is closed.

          The first and second templates 20, 30 can be urged toward the closed position with a predetermined force provided by an urging device 62. The predetermined force can be sufficient to urge a portion of the tubular member 14 to the reference  
30       cross-sectional shape defined by the aperture 40. For example, the urging device 62 can be a weight that is placed on the second template member 30 as shown in Figure 1 to urge the second template member 30 toward the first template member 20, thereby closing the template members 20, 30. The weight 62 is preferably provided at a



predetermined position, i.e., so that a uniform force between the first and second template members 20, 30 can be provided during each subsequent operation of the apparatus 10. In other embodiments of the present invention, the urging device 62 that provides the force for closing the template members 20, 30 can be an actuator such as an electrical, pneumatic, or hydraulic actuator. Alternatively, various other urging devices can be used to provide a force for closing the template members 20, 30 including springs, other configurations of weights, magnets, and the like.

Preferably, the aperture 40 defined by the first and second template members 20, 30 corresponds to the reference size of the tubular member 14 when the template members 20, 30 are configured with a small gap 44 therebetween. The gap 44 can be defined between the first plates 24, 34 of the opposite template members 20, 30 and similarly between the second plates 26, 36 of the opposite members 20, 30. Further, the gap 44 can be defined between the members 20, 30 on both sides of the aperture 40, i.e., between the aperture 40 and the hinge 42 and between the aperture 40 and the measurement device 50. Thus, if the cross-sectional size of the tubular member 14 is about equal to the size of the aperture 40, when the tubular member 14 is provided in the aperture 40, the template members 20, 30 can be adjusted toward the closed position to exert an urging force on the tubular member 14 in the aperture 40. The force provided by the urging device 62 can urge the tubular member 14 to a cross-sectional shape corresponding to the shape of the aperture 40, i.e., the reference shape of the tubular member 14. For example, if the reference shape of the aperture 40 is a circle with a diameter of 9 inches, and the tubular member 14 has a generally circular cross-sectional shape with a diameter of about 9 inches, the tubular member 14 can be urged by the template members 20, 30 to the round shape defined by the aperture 40. If the cross-sectional shape of the tubular member 14 is not round, e.g., defines an eccentric or oval cross-section, the template members 20, 30 can urge the tubular member 14 to the round shape of the aperture 40.

Further, the relative position of the template members 20, 30, when closed against the tubular member 14, is indicative of the cross-sectional size of the tubular member 14. That is, if the tubular member 14 has a cross-sectional size that is greater than the size of the aperture 40, the template members 20, 30 will be closed to a lesser extent, and if the cross-sectional size of the tubular member 14 is less than the aperture 40, the template members 20, 30 will be closed to a greater extent.

Advantageously, the gap 44 provided between the template members 20, 30 can be sufficiently large that the template members 20, 30 can be closed to decrease the size of the aperture 40 to the minimum size of the tubular members 14 that are to be measured in the apparatus 10.

5 By measuring the relative position of the first and second template members 20, 30, the cross-sectional size of the tubular member 14 in the aperture 40 can be determined. For example, the measurement device 50 can be used to determine a gap measurement that corresponds to the size of the gap 44 between the template members 20, 30, and the gap measurement can then be used to determine the diameter  
10 of the tubular member 14. The correlation between the gap measurement and the diameter of the tubular member 14 generally depends on the structure and configuration of the particular apparatus 10. For example, as illustrated in Figure 1, the measurement device 50 is configured to measure the relative position of the template members 20, 30 at a position opposite the aperture 40 from the hinge 42,  
15 though the measurement device 50 can alternatively be configured at other positions.

According to one embodiment of the illustrated configuration, an empirical correlation between the gap measurement and the diameter of the tubular member 14 was determined to be as follows:

$$\text{Diameter of tubular member} = \frac{X}{\pi} \left( \frac{2.3 + D}{15.6} \right) + D$$

20 where X is the gap measurement of the measurement device 50 in inches and D is the diameter of the reference aperture 40. Thus, for template members 20, 30 defining an aperture 40 with a diameter of 4.25 inches, the diameter of the tubular member 14 is equal to (4.25 + 0.134 X). Similarly, for apparatuses 10 having apertures 40 of diameters equal to 6, 9, and 12.75 inches, the diameter of the tubular members 14  
25 measured therewith can be determined according to the following simplified equations:

6-inch diameter apertures: Diameter of tubular member = 6 + 0.169 X

9-inch diameter apertures: Diameter of tubular member = 9 + 0.231 X

12.75-inch diameter apertures: Diameter of tubular member = 12.75 + 0.307 X

30 The measurement device 50 can be configured to display or otherwise report the gap measurement or the particular characteristic of interest of the tubular member 14. For example, the monitoring device 58 can include a liquid crystal display 59, on which

the measurement device 50 can display the gap measurement, i.e., X, in linear measurement units, or the device 50 can perform the necessary mathematical calculation to determine and display the diameter of the tubular member 14.

It is appreciated that the diameters described above are exemplary diameters  
5 corresponding to common duct sizes, but the apparatus 10 can similarly be used to measure tubular members 14 of any size, including very small members and very large members. Further, the correlations described above between the gap measurement of the measurement device 50 and the diameter of the tubular members 14 were developed for a particular apparatus 10 and will likely vary for other  
10 apparatuses, even apparatuses similar in configuration to the one described.

The apparatus 10 can be calibrated before use or between measurement operations. For example, a calibration tool 64 having a predetermined thickness can be positioned between the first and second template members 20, 30. The calibration tool 64 is shown in dashed lines in Figure 2 for illustrative clarity. The second  
15 template member 30 can be closed with the calibration tool 64 positioned between the template members 20, 30 so that the gap 44 therebetween is equal to the thickness of the calibration tool 64. The measurement device 50 can then be adjusted mechanically or electronically until the device 50 reports a gap measurement, diameter, or other measurement corresponding to the calibration tool 64. For  
20 example, the calibration tool 64 can have a first portion defining a thickness corresponding to the gap between the template members 20, 30 when the aperture 40 defines the reference shape, i.e., the desired or nominal cross-sectional shape of the tubular member 14. With the first portion of the calibration tool 64 disposed between the template members 20, 30, the measurement device 50 can be calibrated to the  
25 measurement that corresponds to the reference diameter. Other portions of the calibration tool 64 or different calibration tools can also define other thicknesses. For example, second and third portions of the calibration tool can define thicknesses equal to the gap between the members 20, 30 that correspond to diameters of the aperture 40 that are greater and smaller than the reference diameter, e.g., 0.03 inch greater and  
30 0.03 inch less than the reference diameter. Thus, the second and third portions of the calibration tool 64 can be used to calibrate the measurement device 50 for the corresponding diametrical measuring positions. Alternatively, calibration can be

performed by other methods, e.g., by disposing a member of known cross-sectional shape in the aperture 40 and adjusting the measurement device 50 accordingly.

In operation, the apparatus 10 is configured to urge the tubular member 14 generally to the cross-sectional shape defined by the aperture 40 and determine the diameter or other cross-sectional characteristics of the tubular member 14 with the tubular member 14 so configured. Thus, if the cross-sectional shape of the tubular member 14 does not correspond precisely to the cross-sectional reference shape of the aperture 40, the tubular member 14 is adjusted to the reference shape before measurement. For example, if the reference shape of the aperture 40 is circular, but the tubular member 14 defines a non-round cross section such as an elliptical cross section, the apparatus 10 urges the tubular member 14 to the round cross-sectional shape and determines the diameter of the tubular member 14 when adjusted to the configuration of the reference shape.

Advantageously, the apparatus 10 can also be used to measure a tubular member 14 that defines one or more features. For example, as shown in Figures 3 and 4, the tubular member 14 defines an aperture 16, such as is typically provided for fluidly connecting the tubular member 14 to another tubular member 14 or to an other fluid device. While the aperture would make accurate measurement of the tubular member 14 difficult or impossible using a pi tape or a coordinate measuring machine, the apparatus 10 according to the present invention can measure the diameter of the tubular member 14 proximate to or coincident with the aperture 16, e.g., at the longitudinal position  $D_6$  shown in Figure 3.

Further, while the foregoing discussion describes the determination of the diameter of the tubular member 14, it is also appreciated that other cross-sectional characteristics of the tubular member 14 can similarly be determined. For example, the measurement device 50 can be configured to determine the circumference of the tubular member 14, the cross-sectional area of the tubular member 14, the wall thickness and/or eccentricity of the tubular member 14, and the like.

Figures 5, 5A, and 6 illustrate an apparatus 10 according to another embodiment of the present invention in which a plurality of measurement devices 70 are located circumferentially around the aperture 40. The measurement devices 70 extend radially inward from one or both of the template members 20, 30 and are configured to contact the tubular member 14 when the apparatus 10 is adjusted to the

closed position. For example, the surfaces 25, 27, 35, 37 of the plates 24, 26, 34, 36 that define the aperture 40 can define tooth-like portions 68 that extend radially inward and correspond generally to the circumference of the tubular member 14. As shown in Figure 5A, each of the tooth-like portions 68 defines a radial bore 72  
5 extending through a respective one of the surfaces 25, 27, 35, 37, and a measurement device 70 is disposed in each bore 72 so that a contact end 74 of the measurement device 70 is located slightly radially inward from the corresponding tooth-like portion 68. A mounting end 76 of each measurement device 70 can be mounted in the  
10 respective bore 72, and the mounting end 76 of each device 70 can be connected to the respective template member 20, 30, e.g., by a threaded (screw) mount or other connection. In addition, a slot 78 or other aperture in the plates 24, 26, 34, 36 can provide access to the mounting ends 76 of the measurement devices 70, e.g., through which connection wires 82 from each measurement device 70 can extend. The  
15 apparatus 10 can also include an electronic controller 80 that is configured to process the outputs of the measurement devices 70. For example, the measurement devices 70 can electrically communicate with the controller 80 via the wires 82 that connect each of the measurement devices 70 to the controller 80.

Each of the measurement devices 70 is configured to provide an output that is characteristic of a contact force between the measurement device 70 and the tubular  
20 member 14. Each measurement device 70 can be a sensor that detects force, pressure, and/or strain and generates an electrical signal representative of the force, pressure, or strain. For example, each measurement device 70 can be a diaphragm sensor that includes a diaphragm or membrane fluidly separating a vessel of known reference pressure from a space that is open to the measured pressure. An imbalance between  
25 the measured pressure and the reference pressure deforms the diaphragm of such a sensor, and the deformation can be measured by a strain gage, an indicator needle that is mechanically coupled to the diaphragm, a linear variable differential transformer, or the like. For example, the measurement devices 70 can be miniature stainless steel diaphragm pressure sensors from Entran Devices, Inc. of Fairfield, NJ, such as those  
30 identified as models EPB-BO and EPB-CO. Various other types of sensors can also be used.

The outputs from the measurement devices 70 can be used to determine a measurement of the tubular member 14. In particular, a variation in the wall thickness

of the tubular member 14 can be determined according to the outputs of the measurement devices 70. For example, a variation of the wall thickness around the circumference of the tubular member 14 can affect the stiffness of the tubular member 14. Generally, the wall of the tubular member 14 is stiffer at circumferential locations where the wall of the tubular member 14 is relatively thick, and the wall is less stiff at circumferential locations where the wall is relatively thin. Therefore, by detecting a variation in the outputs of the measurement devices 70 and, hence, the contact forces, the apparatus 10 can detect a variation in the thickness of the wall of the tubular member 14. For example, in operation, the template members 20, 30 can be closed by providing a force  $F$ , as indicated in Figure 5, which can be provided by a weight, actuator, spring, or the like as discussed above.

The apparatus 10 is illustrated in Figure 7 with the tubular member 14 disposed in the aperture 40 and, in particular, with a longitudinal portion indicated by reference label  $D_2$  (Figure 3) disposed in the aperture 40. For purposes of illustrative clarity, the variation in wall thickness around the circumference of the tubular member 14 is shown exaggerated in Figure 7. With the template members 20, 30 in the closed position, as shown in Figure 7, the contact ends 74 of the measurement devices 70 are located in contact with the tubular member 14. The radial location of each of the contact ends 74 can be sufficiently radially inward so that a compressive contact force is exerted by the measurement devices 70 on the tubular member 14, i.e., so that the tubular member 14 is at least slightly deformed by contact with the measurement devices 70. The contact forces between the tubular member 14 and the measurement devices 70 are influenced by the stiffness of the tubular member 14.

The outputs provided by the measurement devices 70 are referred to by reference labels  $R_1$ - $R_{18}$ , as graphically illustrated in Figure 7. Figure 8 illustrates the magnitudes of the outputs  $R_1$ - $R_{18}$  according to the circumferential location of the measurement devices 70. The controller 80 can determine an equation of a line 84 that approximates the relationship between the outputs  $R_1$ - $R_{18}$  and the circumferential location of the measurement devices 70, e.g., using a conventional "best-fit" technique. Further, the controller 80 can use the outputs  $R_1$ - $R_{18}$  to determine a relationship that is illustrative of the thickness of the tubular member 14 at each circumferential location of the devices 70. For example, Figure 9 illustrates the variation in wall thickness of the tubular member 14 as a function of the

circumferential locations of the measurement devices **70**, i.e., according to the outputs **R<sub>1</sub>-R<sub>18</sub>**. The controller **80** can determine the thickness of the tubular member **14** using the outputs **R<sub>1</sub>-R<sub>18</sub>** according to a theoretically determined relationship therebetween, or using a relationship that is derived empirically. For example, an  
5 empirical relationship can be derived by correlating output values from the measurement devices **70** with wall thickness values determined by other measurement techniques such as mechanical measurement, ultrasonic measurement, and the like. The controller **80** can determine an equation of a line **86** that approximates the variation of the wall thickness around the circumference of the tubular member **70**, as  
10 shown in Figure 9.

The eccentricity of the tubular member **14** generally refers to the difference between the maximum wall thickness and the minimum wall thickness at a particular longitudinal position along the length of the tubular member **70**. The eccentricity can be measured at various longitudinal positions of the tubular member **70**. For example,  
15 the eccentricity can be determined at each of the longitudinal positions **D<sub>1</sub>-D<sub>8</sub>** shown in Figure 3. Thus, the eccentricity at longitudinal position **D<sub>2</sub>** is about 7 mm, i.e., the difference between the maximum thickness (14 mm, measured as output **R<sub>9</sub>**) and the minimum thickness (7 mm, measured as outputs **R<sub>1</sub>** and **R<sub>18</sub>**). Figure 10 illustrates a variation of the eccentricity of the tubular member **70** along the longitudinal direction  
20 of the tubular member **70**. The controller **80** can determine an equation of a line **88** that approximates the variation of the eccentricity along the length of the tubular member **70**, as shown in Figure 10.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the  
25 teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for  
30 purposes of limitation.